Technical Report

Department of Defense Best Management Practices for Munitions Constituents on Operational Ranges

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14. ABSTRACT

This document aims to illustrate the environmental risks posed from the deposition of MC residue on ranges from live-fire training activities. Moreover, the document describes the state-of-the-art for numerous management technologies designed to slow or halt the migration of energetic compounds in soil and groundwater. This document is provided in two versions: an extended version that provides full descriptions of all background material and technologies titled, "Department of Defense Operational Range Sustainability through Management of Munitions Constituents" (April 2014), and this compendium document, which is intended as a quick reference guide.

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1 Introduction

Live-fire training is a necessary military function to maintain the mission readiness of our nation's warfighter; however, these training activities can create source zones[1] of munitions constituents (MCs).[2] Some ranges, depending on their hydrogeologic, geographic, and climatological setting, are at a higher risk for the MCs to dissolve and/or migrate through the soil to reach surface water and/or groundwater.

The Department of Defense (DoD) and the Military Services have funded a significant body of basic and applied research to gain a better understanding of the MCs resulting from military training activities on ranges, to characterize the environmental deposition of MCs on military ranges, and to develop technologies to manage or contain MCs in soil and groundwater. The results from these efforts can be found in numerous technical reports and journal articles, but because there is no clearinghouse for this type of information, this information is not readily available to the operational range community. Additionally, there are no guidelines universally accepted by the range managers to implement technological strategies to reduce the dissolution and migration of MCs to environmental media.

1.1 Purpose and Scope

This document is designed to serve as a reference tool for Army, Marine Corps, Navy, Air Force and National Guard range managers and their contractors to assist in the evaluation of MC management technologies. It discusses factors to consider in determining whether to implement MC management technologies (Section 2) and summarizes characterization approaches and management technologies designed to reduce the dissolution and migration of energetic compounds (hereafter referred to as Best Management Practices or BMPs) (Section 3). Methodologies and technologies that have been, or are being, tested and validated at the field-scale are summarized.

The focus of this document is on:

- ***Energetic compounds*** (explosives and propellants) on
- ***Operational land-based ranges*** including: hand grenade ranges; antitank rocket ranges; artillery, tank, and mortar ranges; air-to-ground bombing ranges; and explosive ordnance detonation sites on operational ranges.

This document does not address:

- ***Ammonium perchlorate*** (oxidizer used in solid rocket motor propellant)[3],

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1 A *source zone* is defined as a deposit of chemicals, usually in the surface soil, that under certain conditions may create and sustain a contaminant plume.

2 *Munitions constituents (MC):* Any materials originating from unexploded ordnance, discarded military munitions, or other military munitions, including explosive and non-explosive materials, and emission, degradation, or breakdown elements of such ordnance or munitions (10 United States Code [U.S.C.] 2710 [e][4]).

3 Information on technologies to address ammonium perchlorate (in groundwater) and munitions-related metals is readily available in numerous other documents (e.g., ITRC, 2008; Stroo and Ward, 2009; Fabian and Watts, 2005). Currently there are no validated technologies for managing perchlorate in shallow soils on operational ranges; however, several of the technologies presented in Section 3 are applicable for perchlorate in groundwater.

- ***Munitions-related metals***[3],
- ***Technologies applicable to water-based operational ranges***,
- ***Technologies applicable to small arms ranges (SARs)***, with the exception of SAR firing points that may pose problems due to the release of propellants in the environment, or
- ***Policy recommendations*** for the design, siting and construction of new military ranges, although the information presented on the environmental behavior of the energetic chemicals of concern would be valuable when making these decisions

A companion report, *Department of Defense Operational Range Sustainability through Management of Munitions Constituents* (Jenkins and Vogel, 2014), provides detailed information on the types of energetic chemicals found in explosive and propellant formulations used by the DoD, their chemical properties, deposition of energetic residues from DoD testing and training activities, and the environmental fate and transport of energetic chemicals. Additionally, the companion report provides detailed information on each of the BMPs summarized in Section 3.

1.2 DoD Operational Range BMP Workgroup

A DoD Operational Range BMP workgroup was formed to provide input to and review of this document. Representatives from the Office of the Secretary of Defense, Army, Army National Guard, Marine Corps, Navy, and Air Force involved in operational range environmental issues participated in this workgroup led by the DoD Strategic Environmental Research and Development Program (SERDP)/Environmental Security Technology Certification Program (ESTCP) Office.

References

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ITRC (Interstate Technology & Regulatory Council). 2008. Remediation Technologies for Perchlorate Contamination in Water and Soil. March. 217 p.

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Stroo HF, Ward CH, eds. 2009. *In Situ* Bioremediation of Perchlorate in Groundwater. SERDP/ESTCP Environmental Remediation Technology Monograph Series. Springer Science+Business Media, New York, NY, USA. 250 p.

2 When to Implement Munitions Constituent Management Technologies

2.1 Operational Range Life-Cycle

The development of new operational testing and training ranges and the expansion/upgrading of existing ranges follow established design guidelines (e.g., USACE, 2004). Typical steps in the range development process, from conception to the first live-fire training event, are shown in Figure 2.1.

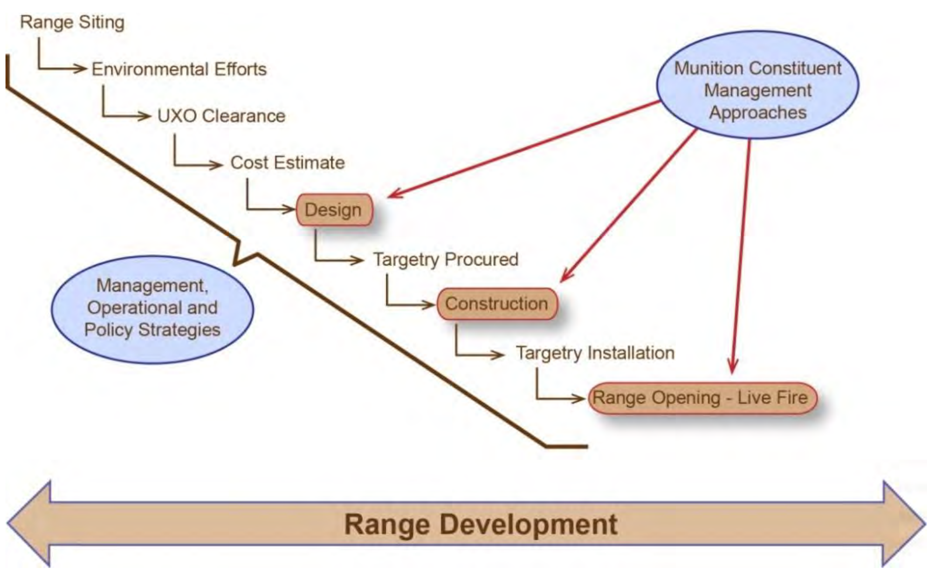

Figure 2-1. Steps in the range development process (adapted from USACE, 2004). ***Note that UXO clearance would not be required in situations where a new range is being developed on virgin land (i.e., land not previously used as a range).***

Energetic residues are deposited in and near impact areas and firing points from live-fire training and from activities at demolition ranges (see Jenkins and Vogel, 2014). Some ranges are much more susceptible to the dissolution and migration of residues to groundwater or surface water than others. The rationale for implementing any of the management technologies summarized in Section 3 should be based on the site-specific hydrogeologic, geographic, and climatological conditions at these ranges. These technologies can be incorporated into the design and construction of new ranges or implemented at existing operational ranges to reduce the risks from energetic compounds reaching groundwater/surface water and migrating off-range.

Management, operational, and policy strategies appropriate to reduce the risk from the deposition, dissolution, and migration of energetic compounds to groundwater should be considered during all stages of range siting, development, expansion, or upgrading. While these types of strategies are not discussed in this document, following are a few examples.

- The high explosive in 155-millimeter (mm) rounds can either be 2,4,6-trinitrotoluene (TNT) or Composition B (hexahydro-1,3,5-trinitro-1,3,5-triazine [RDX]/TNT). RDX does not sorb strongly to soil surfaces and, hence, once dissolved is more mobile in the environment than other explosives such as TNT. A strategy could be developed where TNT-containing rounds are used at the ranges where migration to groundwater is of greater concern and the Composition B rounds (containing RDX) elsewhere.

- The increased use of simulated rounds rather than explosive-filled rounds would reduce the amount of energetic residue deposited.
- Modify current policies to allow explosive ordnance disposal personnel or unexploded ordnance technicians to collect and destroy energetic residue during operational range clearance activities.

2.2 Determining Risk of Munitions Constituents Reaching Groundwater or Surface Water

The purpose of this document is to present technology options to reduce the risk of dissolution and migration of munitions constituents (MCs) to groundwater or surface water once they are deposited on the soil surface. That said, there are some ranges where the technical rationale for investing in these technologies will be more evident than at others due to site-specific hydrogeologic, geographic, and climatological conditions. For example, ranges with substantial concentrations of energetic residues deposited (in the case of existing operational ranges) and continued future residue loading, in areas with high to moderate precipitation, with permeable aquifer material, a shallow to moderate water table or adjacent to sensitive surface water bodies, and slow to moderate moving groundwater would be candidates for MC management technologies (examples shown in Figure 2-2) as opposed to ranges located in arid environments with deep groundwater having a low risk of MCs migrating to groundwater or surface water (Figure 2-3).

Each Service has developed and implemented an Operational Range Assessment Program (ORAP) to assess the potential environmental impacts to off-range receptors from military munitions used on operational ranges and range complexes (USAEC, 2007; HQ USMC, 2009; USN, 2006; USAF, 2006). The objectives of the ORAPs are to (1) determine whether there has been a release or a substantial threat of a release of MCs of concern from an operational range to an off-range area, and (2) whether the release (or substantial threat of release) of MCs of concern to an off-range area creates an unacceptable risk to human health or the environment (DoD, 2005).

Data collected in support of the ORAPs can be useful in qualitatively prioritizing ranges in terms of the risk that energetic compounds will migrate to groundwater or surface water. Examples of data include:

- Description of MC source areas
  - Location of potential sources (e.g., impact areas, firing points, storage, and waste disposal areas)
  - Historical and current munition expenditure data
  - Frequency of clearance activities
- Topographic features/vegetative features
- Surface water features/drainage pathways
- Surface/subsurface geology (soil type/properties)

- Meteorological data related to precipitation, temperature, wind, evapotranspiration rate, and other data bearing on transport
- Geophysical data

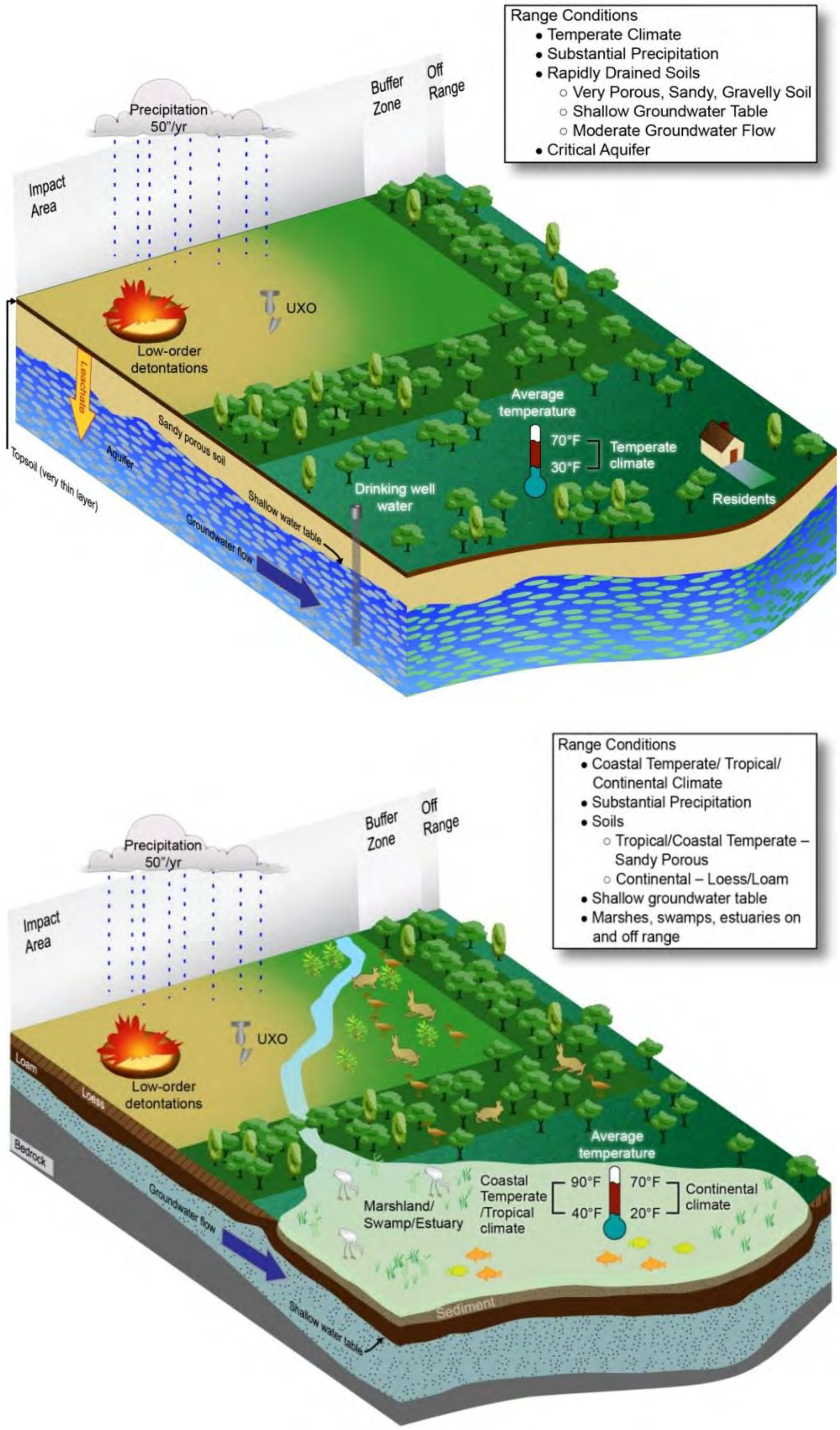

Figure 2-2. High-risk range scenarios.

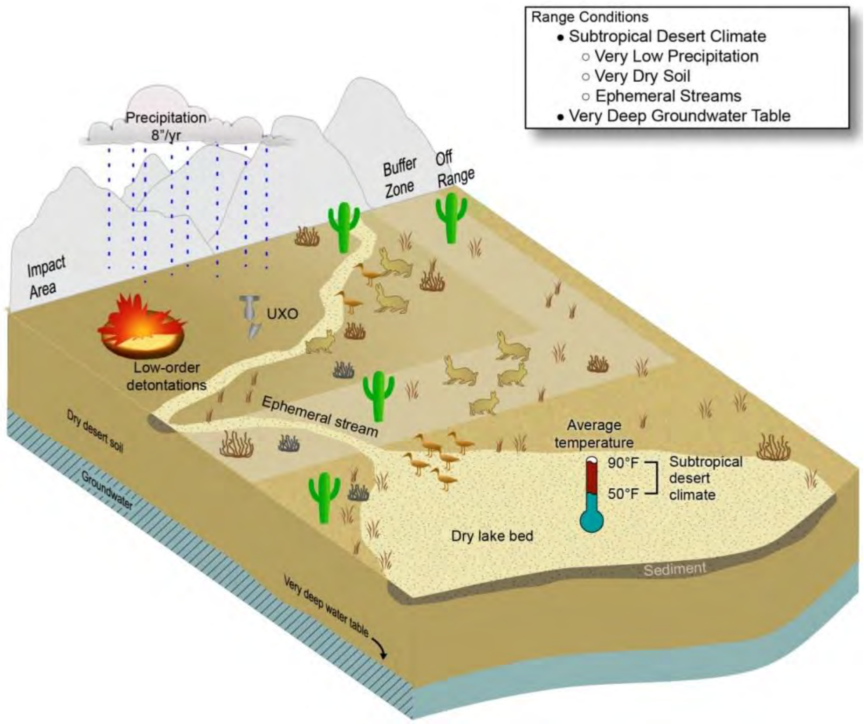

Figure 2-3. Low risk range scenario.

- Hydrogeological data including depth to groundwater, groundwater flow rate (if available), aquifer characteristics, monitoring well logs (if available), and historical sampling and analytical results (if available)
- Site features that have a bearing on transport of MCs

Ranges identified with a higher risk of MCs reaching groundwater or surface water may warrant a more aggressive approach to manage MC dissolution and migration. These sites will require further characterization to better assess the risk and to determine which management technologies are most appropriate.

2.2.1 Risk and Vulnerability Mapping

Land management tools are one approach to provide the decision making information needed to implement MC management approaches and operational changes on ranges. One tool developed by Canadian researchers for use on Canadian Army ranges involves the development of three maps. The first map, called a Vulnerability Map, assesses the vulnerability of various portions of a range to impacts to the underlying aquifer (e.g., the relative ease of dissolved MCs migrating from the ground surface to the upper boundary of the aquifer). The second map, called the Hazard Map, describes the pattern of deposition of MCs on the range due to the placement of firing points, impact areas, and demolition areas. The Vulnerability and Hazard Maps are overlain to produce a Risk Map, which identifies the critical areas of the range complex most susceptible to MC migration to groundwater or surface water.

An example of a Vulnerability Map for Canadian Forces Base (CFB) Wainwright, Alberta, Canada is shown in Figure 2-4. The methodology uses a three-dimensional geologic model to relate vulnerability directly to a conservative estimate of the downward advective time for dissolved MCs to travel from the ground surface to the water table (Ross et al., 2004). The map is color-coded for ease in locating the most vulnerable areas of the range complex. This assessment can provide data useful in siting and planning new ranges to avoid high vulnerability areas or in relocating ranges on existing facilities.

The Hazard Map for CFB Wainwright is shown in Figure 2-5. A Hazard Index is estimated for each training area based on the frequency of use (number of rounds fired, estimate of low-order detonations, amount of residue deposited), environmental fate of the MCs (toxicity, solubility, degradation, and sorption), and the surface area of the training area.

Overlaying the Vulnerability Map with the Hazard Map produces a Risk Map (Figure 2-6) that assigns a level of risk (ranging from very high to very low/no data) that the MCs will reach groundwater or surface water to the different areas of the range complex. This information can be used to identify ranges where MC management approaches (or operational or policy approaches) should be implemented to reduce the risk.

Additional discussion on the approach taken by the Canadian Army to assess environmental risks at their operational ranges is provided in Jenkins and Vogel (2014).

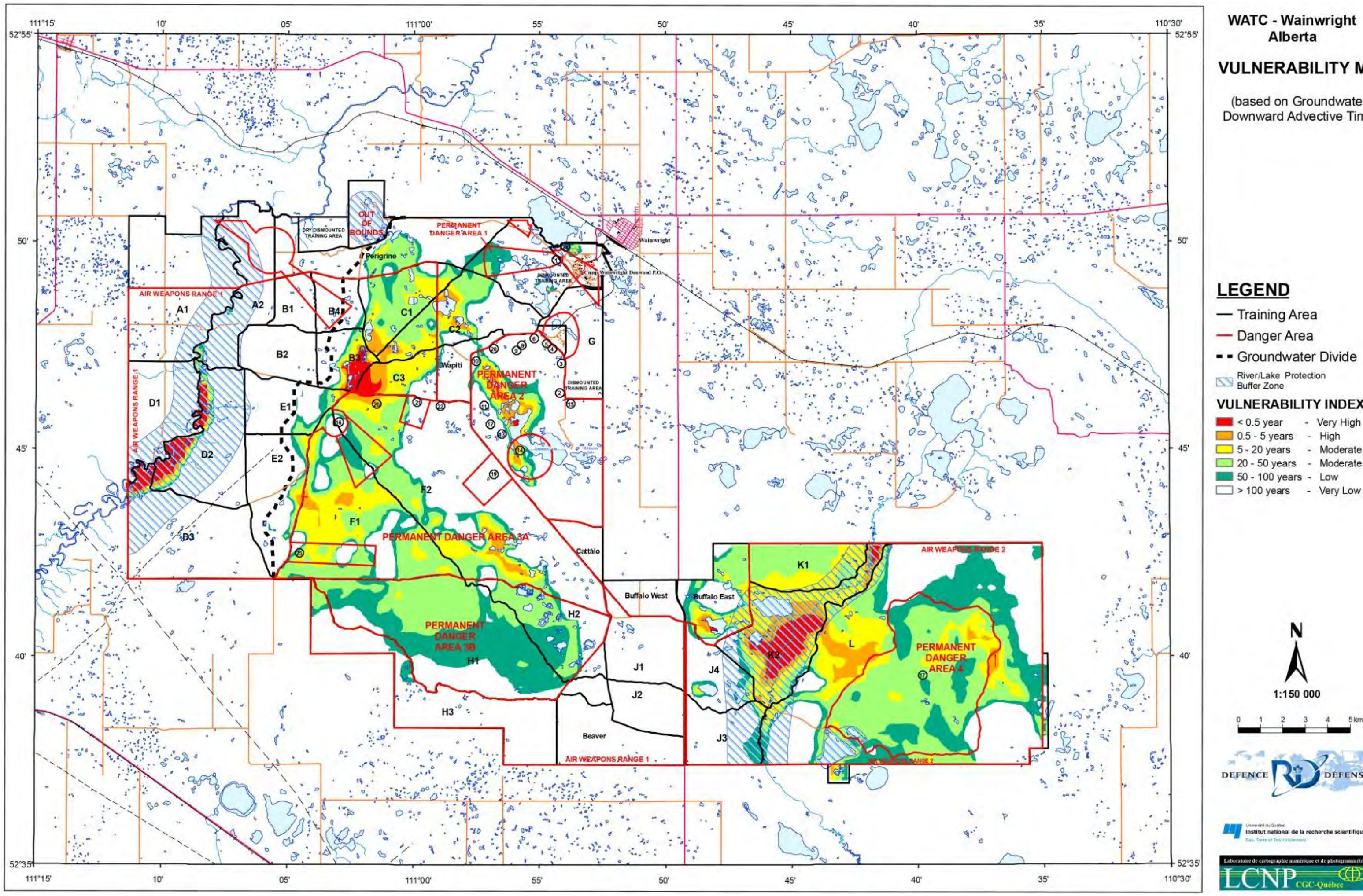

Figure 2-4. Vulnerability Map for CFB Wainwright. Map is provided courtesy of Dr. Sylvie Brochu, Defence Research and Development Canada - Valcartier, Québec, Canada and reprinted with the permission of Director Land Environment from the Canadian Department of the National Defence.

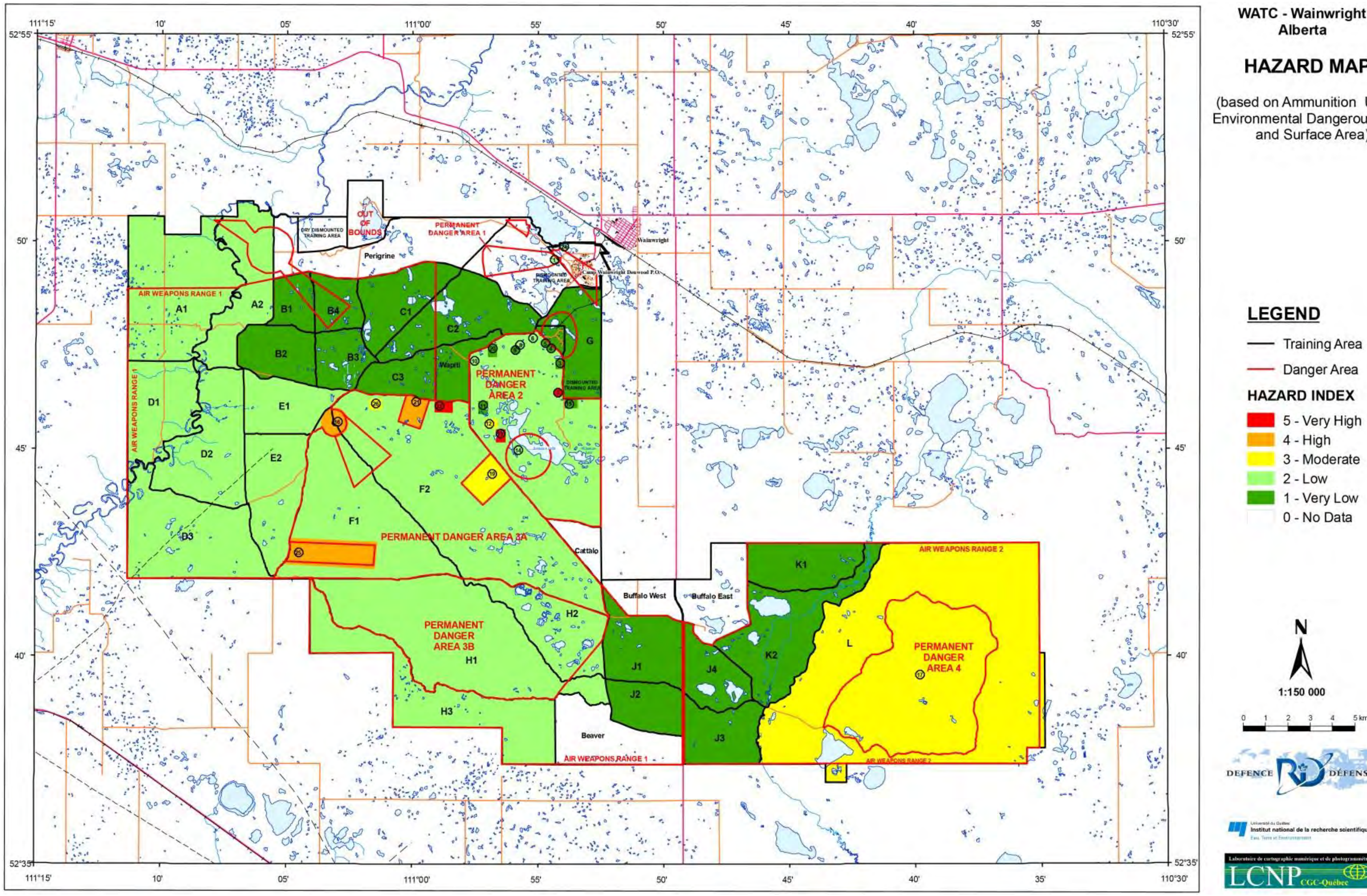

Figure 2-5. Hazard Map for CFB Wainwright. Map is provided courtesy of Dr. Sylvie Brochu, Defence Research and Development Canada - Valcartier, Québec, Canada and reprinted with the permission of Director Land Environment from the Canadian Department of the National Defence.

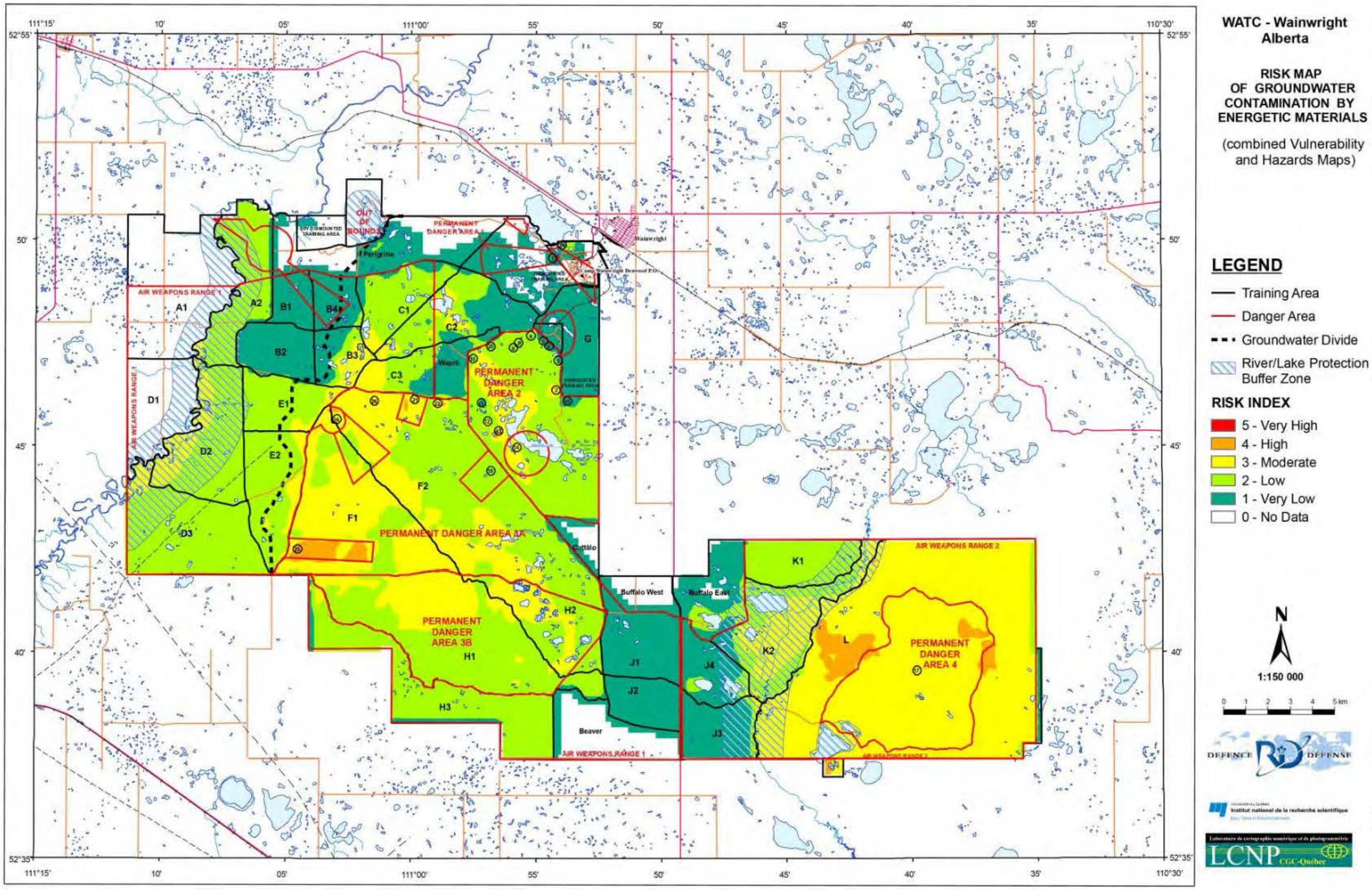

Figure 2-6. Risk Map for CFB Wainwright. Map is provided courtesy of Dr. Sylvie Brochu, Defence Research and Development Canada - Valcartier, Québec, Canada and reprinted with the permission of Director Land Environment from the Canadian Department of the National Defence.

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USAEC (U.S. Army Environmental Command). 2007. Army Operational Range Assessment Protocol; Phase I (Qualitative) Range Assessments (Interim). March. 68 p.

USN (U.S. Navy). 2006. U.S. Navy Range Sustainability Environmental Program Assessment (RSEPA) Policy Implementation Manual (Rev. 1). November.

3 Characterization Technologies and Best Management Practices (BMPs) for Munitions Constituents

This section summarizes information on (1) characterization technologies used to support the selection and implementation of munitions constituent (MC) BMPs and (2) the technical approaches used to mitigate the dissolution and transport of munitions constituents.

In order to determine if and how energetic residues need to be managed, the mass loading for the specific area (e.g., impact area, areas behind firing points) must be estimated. The best means of doing so is to conduct a soil sampling effort and calculate the mass loading from the soil concentration estimates. Section 3.1 describes the *MULTI INCREMENT*®[4] sampling (MIS) approach to collecting representative near-surface soil samples within an area of interest.

In instances where it is not possible to obtain characterization data, an estimate of the loading rate can be calculated based on the military expenditure rates for the munitions used at the range and the tabulated dud and low-order rates. An example of an approach that can be used to make this calculation is the MC Loading Rate Calculator contained in the Marine Corps Range Environmental Vulnerability Assessment (REVA) Users Guide (U.S. Marine Corps, 2006). See Section 4.3.2.2 of the companion document titled, *Department of Defense Operational Range Sustainability through Management of Munitions Constituents* (Jenkins and Vogel, 2014), for additional discussion on using this approach.

In some cases, it may be advantageous to install groundwater monitoring wells within the confines of an operational range. The advantage is that the question of whether energetic compounds are impacting groundwater can be addressed directly and not be the subject of speculation. The installation of groundwater wells on an operational range is discussed in Section 3.2.

Sections 3.3 through 3.14 present BMP fact sheets on technical approaches to mitigate the dissolution and transport of energetic residues in soil and groundwater. Some of the approaches presented have been demonstrated and validated at operational ranges and have documented cost and performance data (e.g., alkaline hydrolysis [liming], hydraulic control). Other technologies, such as active *in situ* management of groundwater or monitored natural attenuation, have been shown to be effective for managing energetic compounds; however, to date, they have only been implemented at non-range sites (e.g., munition manufacturing facilities). Finally, some of the approaches presented are still in the development phase and not yet ready for full-scale implementation on an operational range.

Each BMP fact sheet provides a description of the technology or approach, identifies the types of ranges where it can be used, its advantages and disadvantages, cost information (if available), and key references. Additional information on each of the following characterization technologies and BMPs can be found in the companion report, *Department of Defense Operational Range Sustainability through Management of Munitions Constituents* (Jenkins and Vogel, 2014).

[4] *MULTI INCREMENT*® is a registered trademark of EnviroStat, Inc. of Fort Collins, Colorado (http://www.envirostat.org/, accessed March 6, 2014).

- Supporting Technologies
  - Surface Soil Sampling (Section 3.1)
  - Groundwater Characterization (Section 3.2)
- Soil Mitigation Approaches
  - Alkaline Hydrolysis (Liming) (Section 3.3)
  - Passive *In Situ* Management Approach for Shallow Soil (Section 3.4)
  - Plant-Based Mitigation (Section 3.5)
  - *Ex Situ* Soil Management (Section 3.6)
  - Use of Fire to Destroy Energetic Particles (Section 3.7)
  - Onsite Residue Collection and Destruction (Section 3.8)
  - Field Portable Burn Pan (Section 3.9)
- Groundwater Mitigation Approaches
  - Monitored Natural Attenuation (Section 3.10)
  - Passive *In Situ* Mitigation Approach for Groundwater (Section 3.11)
  - Active *In Situ* Management Approach for Groundwater (Section 3.12)
  - Hydraulic Control (Section 3.13)
  - Constructed Wetlands (Section 3.14)

UXO Avoidance: Almost all of the technologies described in the following fact sheets will require physical access to the area of interest on the range (e.g., impact areas). Before any intrusive activities are conducted within an area that could have buried unexploded ordnance (UXO) present, UXO avoidance activities must have been completed. Initially, qualified personnel (explosive ordnance disposal [EOD] or UXO technicians) will clear pathways to proposed sampling locations. This is usually done using magnetometers. The pathways must be wide enough for safe passage of drilling equipment (if necessary) and personnel; generally a distance of twice the width of the widest vehicle is used. The route must be clearly marked. Should a potential UXO anomaly be detected, the location will be clearly identified, and the route and potential drilling location will be moved appropriately. Specific details on clearance requirements and UXO avoidance regulations can be obtained by contacting the U.S. Army Corps of Engineers (USACE), Military Munitions Center of Expertise (Huntsville, Alabama). DoD Manual 6055.09-M, Volume 7 (DoD, 2008) provides the requirement to perform construction support and ordnance avoidance. Army Pamphlet EP 75-1-2 (U.S. Army, 2004) provides procedural guidance for munitions and explosives of concern (MEC) support during hazardous, toxic, and radioactive waste (HTRW) and construction activities.

References

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U.S. Marine Corps. 2006. Range Environmental Vulnerability Assessment (REVA) User's Guide. Headquarters Marine Corps, 2 Navy Annex, Washington, DC, USA. November.

3.1 MULTI INCREMENT® Sampling (MIS) Approach for Surface Soil

Coring tool designed specifically for collecting cohesive multi-increment soil samples (M.R. Walsh, 2004).

Description: The *MULTI INCREMENT®* sampling (MIS)[1] approach is used to estimate the mean concentration and estimate of uncertainty for energetic compounds in soil within a sampling unit. Samples are built by combining a number of increments of soil from within the sampling unit to obtain a ~1-kilogram sample. The increments can be collected in a totally random fashion or more systematically. In the systematic-random approach, a random starting point is selected within the sampling unit and increments are gathered on an even spacing as the sampler walks back and forth from one corner of the sampling unit to the opposite corner. In this way, increments of soil from all areas of the sampling unit are included and no area is oversampled. The mean concentration values are used to estimate the mass of each energetic compound found within the sampling unit (see Jenkins and Vogel, 2014, Section 4.2).

Where It Can Be Used: To date, the MIS approach has been applied to sampling units up to 100 meters (m) × 100 m. The approach can be used at firing points, direct line-of-fire impact areas (e.g., antitank ranges), hand grenade ranges, blow-in-place detonations, and observed individual low-order detonations. Multiple sampling units may be needed at indirect fire impact areas. Recommendations for sampling unit sizes for various types of military training ranges and the number of increments per sample are available in USEPA, 2012.

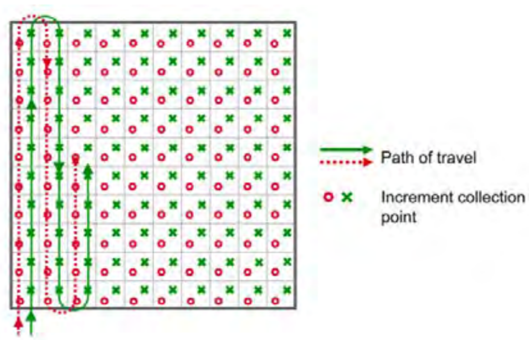

Illustration of MIS using a systematic-random sampling design for collecting two separate 100-increment samples.

Advantages: Soil samples collected using the MIS approach are more representative of energetic compound concentrations within a sampling unit than those collected using a discrete sampling approach. MIS addresses concerns due to the extreme heterogeneous distribution of energetic residues on ranges. The heterogeneity is due to the presence of particles of energetic residues. The variability among replicate samples collected by the MIS approach has been shown to be much lower than for replicate discrete samples taken within the same sampling units.

Cautions: No chunks of energetic compounds or soil samples containing 2,4,6-trinitrotoluene (TNT) or hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) in excess of 10% can be shipped offsite. Onsite methods can be used to ensure that soil samples are below the 10% level (EPA SW846 Methods 8510 [USEPA, 2007] and 8515 [USEPA, 1996]).

Cost Information: Very little information has been published on the cost of range characterization using MIS. However, Nieman and Downs (2012) published the cost for range characterization using MIS and the proper laboratory analytical procedures (SW846 Method

8330B) for the Thermal Treatment Area, Hill Air Force Base, Utah. The total cost of characterization of 780,000 m^2 (192 acres) was estimated to be $263,000. This effort consisted of sampling 95 100-m × 100-m grid cells, yearly, over a five-year period.

***Recommendation:* Recommended characterization method to provide representative energetic compound concentrations in surface soil within areas of interest (e.g., sampling units) on an operational range.**

Key Resources:

Jenkins T, Vogel C. 2014. Department of Defense Operational Range Sustainability through Management of Munitions Constituents. Prepared for the DoD Environmental Security Technology Certification Program, Alexandria, VA, USA.

Nieman KC, WC Downs. 2012. Case Study: Implementation of Method 8330B for Explosives Residue Characterization at the Utah Test and Training Range. In USEPA Federal Facilities Forum (FFF) Issue Paper: Site Characterization for Munitions Constituents. EPA-505-S-11-001. Prepared by Jenkins TF, Bigl SR, Hewitt AD, Clausen JL, Craig HD, Walsh ME, Martel R, Nieman K. Taylor S, Walsh MR for the USEPA FFF, Washington, DC, USA. January. Appendix A2.

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[1] *MULTI INCREMENT*® is a registered trademark of EnviroStat, Inc. of Fort Collins, Colorado (http://www.envirostat.org/, accessed March 6, 2014).

3.2 Groundwater Characterization

Installation of groundwater monitoring well at Canadian Forces Base Shilo, Manitoba, Canada (courtesy of Sonia Thiboutot, Defence Research and Development Canada – Valcartier, Québec, Canada).

Description: Process to install a flush mounted groundwater well within or near areas of interest on a range to allow for the collection and analysis of groundwater samples. Wells can be installed using a hollow stem auger or a direct push method depending on the geology and stratigraphy of the given location.

Where It Can Be Used: At areas of concern within or on the boundary of operational ranges to allow monitoring to determine whether energetic compounds have impacted groundwater. This approach has been used at military impact ranges across Canada (Bordeleau et al., 2008; Martel et al., 2009).

Advantages: Provides the ability to monitor energetic compounds (and other water quality parameters) in groundwater in or near areas of concern. It has been shown that the use of flush mounted wells greatly reduces the likelihood that these wells will be destroyed or damaged when installed within impact areas (Bordeleau et al., 2008; Martel et al., 2009). Groundwater data obtained from these wells can be used in predictive models to determine the fate and transport of the energetic compounds and aid in determining if implementation of BMPs is warranted.

Disadvantage: Before any intrusive investigations are conducted within an area that could have buried unexploded ordnance (UXO) present, UXO avoidance activities must be completed. In general, a sufficiently large area will be cleared at the sampling location to allow the drilling equipment to maneuver properly. At minimum, an area with a 25-foot radius from the bore hole location will be cleared and clearly marked. At all drilling locations, downhole avoidance techniques are required. Also see references on UXO avoidance provided in Section 3 of this document.

Cost Information: General information about well construction and development can be found in ASTM D5092-04(2010)e1 (ASTM, 2010a) and ASTM D5521-05 (ASTM, 2005). Very little information has been published on the cost of installing flush mount groundwater monitoring wells within an impact area. The actual drilling costs should not differ from that of installing flush-mounted monitoring wells at non-range sites; however, the cost of UXO avoidance activities will drive up the total costs.

Recommendation: **For sites with a high risk of energetic compounds reaching groundwater and migrating off-range, installation of groundwater wells is recommended within or adjacent to the area of interest.**

Key Resources:

ASTM. 2010a. Standard Practice for Design and Installation of Groundwater Monitoring Wells. ASTM D5092 - 04(2010)e1. Available at http://www.astm.org/Standards/D5092.htm, accessed March 6, 2014.

ASTM. 2010b. Standard Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers. ASTM D6725 - 04(2010). Available at http://www.astm.org/Standards/D6725.htm, accessed March 6, 2014.

Bordeleau G, Martel R, Ampleman G, Thiboutot S. 2008. Environmental impacts of training activities at an air weapons range. *J Environ Qual* 37:308-317.

Martel R, Mailloux M, Gabriel U, Lefebvre R, Thiboutot S, Ampleman G. 2009. Behavior of energetic materials in groundwater at an anti-tank range. *J Environ Qual* 38:78-92.

3.3 Alkaline Hydrolysis (Liming)

Using an all-terrain vehicle and a drop spreader to apply lime to soil surface at a HGR (Larson et al., 2007).

Description: Alkaline hydrolysis (e.g., liming) involves the application of hydrated lime to surface soils containing energetic residues. The increased alkalinity, caused by the lime addition to the soil, results in the transformation of 2,4,6-trinitrotoluene (TNT) and hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) to less mobile products, reducing the potential for migration in the soil.

Where It Can Be Used: This approach has been shown to be successful in several field demonstrations for managing energetic residues in soil at hand grenade ranges (HGRs) and demolition ranges. The lime and energetic residues must be in solution for the transformation reactions to occur. Thus, ranges located in arid environments are not suited for this approach due to lack of precipitation.

Advantages: This is an inexpensive, easy to implement approach for managing energetic residues at small ranges. For ranges not accessible for troop maneuvers, there seems no occupational health issues associated with this technology.

Disadvantages: The addition of hydrated lime and modification of the surface soil pH must be compatible with National Environmental Policy Act (NEPA) requirements and not pose other environmental concerns (e.g., endangered species). Hydrated lime is much less effective for the management of residues of octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) and 2,4-dinitrotoluene (2,4-DNT) than for RDX and TNT and would be less effective at antitank rocket range impact areas where HMX is the predominant residue present. Additionally, caution should be used if implementing alkaline hydrolysis for aluminum-containing explosives, such as tritonal or Composition H6, due to the potential to generate hydrogen gas, which could become a safety concern. The use of hydrated lime in areas where troops maneuver, as in some Marine Corps ranges, may not be appropriate due to potential health risks.

Application Frequency: Generally, it is recommended that hydrated lime be applied twice per year at HGRs, and that the lime should be tilled into the soil to a depth of 6 inches. (*Note: Safety concerns must be paramount—lime application should only occur after an area has been cleared by Explosive Ordnance Disposal [EOD] personnel*). However, site-specific factors such as range usage, soil type, and amount of rainfall will influence the required application frequency.

Cost Information: The cost for implementation of the alkaline hydrolysis technology at an HGR is approximately $15,000/year/hand grenade bay. These costs were based on a conservative assumption of reapplication of lime being required on a quarterly basis. Factors such as presence of unexploded ordnance (UXO), whether application equipment is rented or purchased, and the amount of rainfall and soil type will impact this estimated cost. The cost of implementing alkaline hydrolysis at an open burn/open detonation (OB/OD) range is estimated to be $2400/acre with an additional cost of $1200 per detonation event treated.

Recommendation: **Recommended for the management of energetic residues at HGRs and demolition ranges.**

Key Resources:

ESTCP. 2008. Grenade Range Management Using Lime for Metals Immobilization and Explosives Transformation. ESTCP Cost and Performance Report for ER-0216. August.

ESTCP. 2012. Open Burn/Open Detonation (OBOD) Area Management Using Lime for Explosives Transformation and Metals Immobilization. ESTCP Cost and Performance Report for Project ER-200742. October.

Johnson JL, Felt DR, Martin WA, Britto R, Nestler CC, Larson SL. 2011. Management of Munitions Constituents in Soil Using Alkaline Hydrolysis: A Guide for Practitioners. ERDC/EL TR-11-6. U.S. Army ERDC, Vicksburg, MS. October.

Larson SL, Davis JL, Martin WA, Felt D, Nestler CC, Fabian G. 2007. Implementation Guidance Manual: Grenade Range Management Using Lime for Dual Role of Metals Immobilization and Explosives Transformation. ESTCP ER-0216. Performed by U.S. Army ERDC, Vicksburg, MS for the ESTCP, Arlington, VA.

3.4 Passive In Situ Management Approach for Shallow Soil

Application of PMSO material to HGR Bay 1, Remagen Grenade Training Range, Fort Jackson, South Carolina (Fuller and Schafer, 2010).

Description: Applying biological amendments to surface soils has the potential to sorb, transform, and/or mineralize energetic contaminants at military ranges, thereby reducing the potential for residue migration to groundwater or surface water resources. 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) can be sorbed onto organic substrates, reducing their rate of migration. The presence of readily degradable organic material can stimulate microbial activity, thereby reducing the oxygen concentration and driving the environment anaerobic. Under this condition, TNT is reduced and can be irreversibly bound to the organic substrate, and RDX (and perhaps HMX) can be mineralized.

Where It Can Be Used: This approach is currently under development for use at ranges where energetic residues have been deposited over a small area (e.g., mortar and grenade ranges, tank target areas, and open burn/open detonation [OB/OD] areas).

Advantages: The major potential advantage of the amendments currently under development is the ability to apply them via spraying them onto the soil surface without the need to till them into the profile. This would allow the use of this management option at ranges with unexploded ordnance (UXO) still present.

Disadvantages: The main disadvantages of the passive *in situ* shallow soil management approaches that have been tested to date are the potential need to apply amendments frequently, the flammability of some amendments, and a possible increase in dust emissions, although a new approach being evaluated may significantly reduce these disadvantages.

Cost Information: Costs for the implementation and maintenance of a buried peat moss/soybean oil (PMSO) layer 2 feet below ground surface at a hand grenade range (HGR) have been estimated (ESTCP, 2010; Fuller and Schafer, 2010). However, to the authors' knowledge, implementation of a shallow, buried layer of PMSO has not been field-tested to date; thus, operational and logistical challenges may hinder implementation of this approach at some sites. New amendments that can be applied directly to the soil surface (without grading or tilling) are currently being developed (Borden, 2011). Cost and performance information will be posted to the Strategic Environmental Research and Development Program (SERDP) /Environmental Security Technology Certification Program (ESTCP) website when available.

***Recommendation:* Although still in the demonstration/validation phase of development, passive *in situ* shallow soil management appears to have the potential to be a very useful approach for the control of energetic residues at both small and large ranges.**

Key Resources:

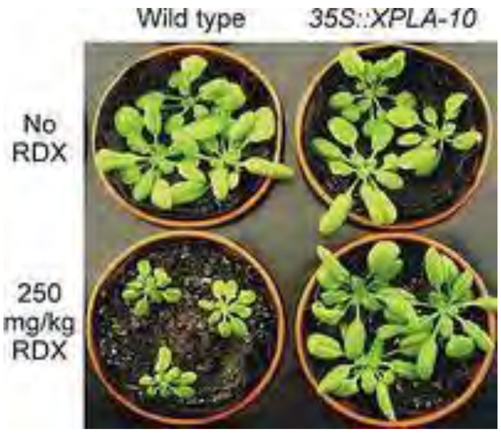
Borden R. 2011. Generation of Biodegradation-Sorption Barriers for Munitions Constituents. ESTCP Project No. ER-201123 Fact Sheet. Available at http://www.serdp.org/, accessed March 6, 2014.

Fuller ME, Schafer CE. 2009. Treatment of Explosives Residues from Range Activities. ESTCP Project No. ER-0434 Final Report. September. 354 p

Fuller ME, Schafer CE. 2010. In Place Soil Treatments for Prevention of Explosives Contamination. ESTCP Project No. ER-0434 Grenade Range Final Report. January. 225 p.

ESTCP. 2010. Treatment of Explosives Residues from Range Activities. ESTCP Project No. ER-0434 Cost and Performance Report. January. 73 p.

3.5 Plant-Based Mitigation



Wild type and transgenic plants expressing a novel RDX-degrading gene (XplA) growing on soil with and without RDX. The transgenic plants show minimal signs of toxicity and removed significant amounts of RDX from the soil (Bruce, 2012)

Description: Plant-based mitigation refers to the direct use of plants to detoxify munitions constituents in soil or groundwater by destruction or stabilization. Normal plants are capable of taking up large quantities of hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), but do not destroy these chemicals and can release them at a later date. Incorporation of genes from microorganisms into plants that have the ability to destroy these chemicals might offer a long-term management approach to reducing the most mobile contaminants in soil at ranges.

Where It Can Be Used: Once fully developed, this technology would be applicable to large ranges, such as artillery or bombing ranges, and could provide a long-term strategy for reduction of energetic residues.

Advantages: The major advantage of this technology is the possible implementation at large ranges where engineered plants could be established to manage energetic residues and minimize leaching over an extended time periods.

Disadvantage: The major issue is the need to develop transgenic plants because native plants generally do not destroy energetic compounds that are taken up into the plant. The second disadvantage is the toxicity of 2,4,6-trinitrotoluene (TNT) to plants, which is generally co-resident in areas with RDX contamination.

Cost Information: No cost information is currently available for the full-scale application of this technology.

Recommendation: Although not sufficiently developed at present for implementation, this technology has the potential for application at large military impact areas if suitable transgenic plants can be developed and a means of distribution demonstrated. Refer to the SERDP/ESTCP website for updates on currently funded plant-based mitigation projects.

Key Resources:

Best EPH, Smith JC, Ringelberg DB. 2009. Phytoremediation of Composition-B Derived TNT and RDX in Herbaceous Plant-Vegetated and Bare Lysimeters. ERDC TR-09-10/SERDP Project ER-1500 Final Report. December. 102 p.

Bruce N. 2012. Sustainable Range Management of RDX and TNT by Phytoremediation with Engineered Plants. SERDP Project ER-1498 Fact Sheet.

Schnoor J. 2011. Phytoremediation for the Containment and Treatment of Energetic and Propellant Material Releases on Testing and Training Ranges. SERDP Project ER-1499 Final Report. June. 169 p.

Shanks JV. 2007. Genetic and Biochemical Basis for the Transformation of Energetic Materials (RDX, TNT, DNTs) by Plants. SERDP Project ER-1319 Final Report. April. 558 p.

Strand S, Bruce N. 2009. Engineering Transgenic Plants for the Sustained Containment and In Situ Treatment of Energetic Materials. SERDP Project ER-1318 Final Report. June. 103 p.

3.6 Ex Situ Soil Management

Compost windrow being turned by a windrow turner at Plum Brook Ordnance Works, Sandusky, Ohio (USACE, 2011).

Description: The practice of excavating soil containing energetic chemicals and mixing it with a degradable carbon source, microorganisms, and/or nutrients in an aboveground pile, windrow, or reactor. The technologies rely on biological processes to transform the contaminants, generally to break down the energetic chemicals to intermediates that can be mineralized or bound irreversibly to the organic material in the soil.

Where It Can Be Used: These *ex situ* technologies have primarily been used to manage small volumes of heavily-contaminated soil, such as those found at ammunition plants and explosive manufacturing sites. They might have utility in areas where small volumes of soil have been impacted by low-order detonations or where repeated detonations occur.

Advantages: By excavating the impacted soil and managing *ex situ*, the risk of dissolution and migration of the energetic chemicals is eliminated.

Disadvantage: These technologies have typically been applied to smaller volumes of heavily-impacted soil. To manage larger volumes of less contaminated soils would likely require process changes in some cases. Implementation of these *ex situ* approaches requires that the soil be excavated prior to management, something that may be dangerous when working in areas with unexploded ordnance (UXO). With the bioslurry technology, the slurry requires dewatering prior to disposal, which adds to the overall management cost.

Cost Information: Cost estimates for the *ex situ* technologies discussed in this section are as follows:

- Windrow composting – $206–$1,025/ton soil
- Bioslurry reactors – $309/ton soil
- Biopiles – $205/ton soil
- Landfarming – $90–$150/ton soil

***Recommendation:* These technologies are recommended primarily for high-concentration, low-volume applications at sites where the soil can be excavated. These *ex situ* approaches may have application at demolition ranges where repeated use has resulted in fairly high concentrations of energetic contaminants in a fairly small volume of soil or at hand grenade ranges (HGRs).**

Key Resources:

Jerger DE, Woodhull PM. 2000. Applications and Costs for Biological Treatment of Explosives-Contaminated Soils in the US. In Spain JC, Hughes JB, Knackmuss H-J (eds) Biodegradation of Nitroaromatic Compounds and Explosives. Lewis Publishers, Boca Raton, FL, USA. Chap. 14.

Lewis TA, Newcombe DA, Crawford RL. 2004. Bioremediation of soils contaminated with explosives. *J Environ Manag* 70:291-307.

USACE. 2011. Soil Composting for Explosives Remediation: Case Studies and Lessons Learned. Public Works Technical Bulletin 200-1-95. May 17.

3.7 Use of Fire to Destroy Energetic Particles on Surface Soils

Description: The use of controlled burning to reduce the mass of energetic residues present on range surfaces. Explosives such as 2,4,6-trinitrotoluene (TNT) and hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) are unstable at high temperatures and it appears that temperatures at the soil surface during range fires may be hot enough to destroy explosives deposited on the surface as particles from low-order detonations.

Where It Can Be Used: The amount of energetic residue reduction achieved is a function of the maximum temperature achieved and the duration of that temperature. The level of available fuel will determine these parameters. For most sites, the native mass of vegetation present will be insufficient to achieve these conditions and additional fuel will be needed.

Advantages: Energetic residues present at the surface can be destroyed using this technique as well as any energetic residue present in aboveground vegetation. Large pieces of residue that would be present just after the occurrence of a low-order detonation appear to be consumed by fire to a greater extent than small particles on the soil surface.

Challenges/Disadvantages: For most sites, additional fuel will have to be supplied to the site. How feasible this might be for a given location and range size is very site-specific. In general, subsurface residues will be minimally affected. If the temperature developed in the burn is insufficient to destroy the residues, melting and downward transport of TNT and perhaps other analytes associated with the TNT is possible. Obtaining regulatory approval for a controlled burn may present challenges due to air emission concerns.

Cost Information: Not available. Full-scale controlled burns have not been implemented for the purpose of destroying explosives residues at training ranges.

***Recommendation:* This technology has the potential to reduce the mass of energetic residues at impact ranges and antitank rocket range firing points. This approach is one of the few technologies that could be implemented fairly easily over a large area, such as at an artillery or bombing range. It could be used in conjunction with some form of plant-based mitigation approach to destroy energetic compounds that have been taken up into plants.**

Key Resources:

Battelle, Integrated Science and Technology, Inc., University of Rhode Island. 2006. Impacts of Fire Ecology Range Management (FERM) on the Fate and Transport of Energetic Materials on Testing and Training Ranges. SERDP CP-1305 Final Report. Prepared for the SERDP, Arlington, VA, USA. Available at http://www.serdp.org/, accessed March 6, 2014.

Poulin I. 2011. Remediation of Surface Soils Contaminated with Energetic Materials by Thermal Processes. In Chappell MA, Price CL, George RD, eds, Environmental Chemistry of Explosives and Propellant Compounds in Soils and Marine Systems: Distributed Source Characterization and Remedial Technologies. American Chemical Society, Washington, DC, USA. Chapter 20.

Price RA, Bourne M. 2011. Effects of Wildfire and Prescribed Burning on Distributed Particles of Composition-B Explosive on Training Ranges. In Chappell MA, Price CL, George RD, eds, Environmental Chemistry of Explosives and Propellant Compounds in Soils and Marine

Systems: Distributed Source Characterization and Remedial Technologies. American Chemical Society, Washington, DC, USA. Chapter 19.

3.8 Onsite Residue Collection and Destruction

Ruptured 155-millimeter (mm) round at Fort Bliss, New Mexico; the red chunks in front of the round are 2,4,6-trinitrotoluene (TNT) (from Jenkins et al., 2005).

Description: The practice of collecting and destroying chunks of energetic chemicals at ranges by explosive ordnance disposal (EOD)/unexploded ordnance (UXO) personnel to reduce the mass of energetic residues in source zones thereby preventing their dissolution and migration.

Where It Can Be Used: Currently, the collection and destruction of chunks of energetic chemicals have not been implemented for environmental purposes. Some of the Military Services conduct routine range clearance activities to destroy UXO items present on the surface. Sometimes during clearance activities, large chunks of energetic compounds are collected and detonated to remove explosive hazards from these ranges. These activities are not designed to reduce the mass of energetic residues at ranges, but have that effect as a side benefit.

Advantages: The major advantage of this approach is its effectiveness in reducing the mass of energetic residues in source zones. Collecting large pieces of residue and destroying it using an explosive charge or in another manner is the least expensive means of preventing the dissolution and migration of the residues. A few large chunks of residue that contain 1 kilogram (kg) hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), when dissolved, has the potential to contaminate 500 million liters (L) of water to 2 micrograms per liter (µg/L) (U.S. Environmental Protection Agency [USEPA] health advisory), assuming no natural attenuation occurs.

Disadvantage: Several U.S. Department of Defense (DoD) and Service Instructions currently prevent or limit the ability of EOD personnel to remove energetic residues from ranges during operational range clearance activities.

Cost Information: Not available.

Recommendation: **Recommended for the management of energetic residues at artillery, mortar, bombing, and antitank rocket range impact areas. Implementation would require modifications to current DoD and Service policy.**

Key Resources:

Brochu S, Thiboutot S, Lewis J, Ampleman G, Brousseau P. 2004. Estimation of the Quantity of Explosive Residues Resulting from the Detonation of Unconfined Explosives Charges. In Distribution and Fate of Energetics on DoD Test and Training Ranges: Interim Report 4. ERDC TR-04-4. U.S. Army ERDC, Vicksburg, MS, USA. Chapter 7.

Jenkins TF, Thiboutot S, Ampleman G, Hewitt AD, Walsh ME, Ranney TA, Ramsey CA, Grant CL, Collins CM, Brochu S, Bigl SR, Pennington JC. 2005. Identity and Distribution of Residues of Energetic Compounds at Military Live-Fire Training Ranges. ERDC TR-05-10. U.S. Army Engineer Research and development Center, Vicksburg, MS, USA. November.

Thorne PG. 2004. On-Range Treatment of Ordnance Debris and Bulk Energetics Resulting from Low-Order Detonations. SERDP Final Report CP-1330. Prepared for SERDP, Arlington, VA, USA. Available at http://www.serdp.org/, accessed March 6, 2014.

3.9 Field Portable Burn Pan

Propellant burn pan test, Firing Point Neibar, Fort Richardson, Alaska, March 2011 (Walsh et al., 2011).

Description: Burn pans are portable devices that allow propellant charges to be loaded and burned in a controlled setting. When training with large-caliber weapon systems (e.g. howitzers, mortars), a full complement of propellant charges is issued with each round. However, the charges are seldom fully utilized during training. Excess propellant charges are disposed of by burning on the ground, which creates propellant residues.

Where It Can Be Used: Ranges where large caliber weapons are fired.

Advantages: Field disposal of excess propellants is an integral part of field artillery training. Use of burn pans increase the efficiency of propellant disposal and greatly reduce the deposition of explosives and heavy metals in soils. Portable burn pans allow troops to train as they fight without compromising range sustainability.

Limitations: Portable burn pans are designed for burning up to 120 kilograms of propellant charges. The turn-around time between batches is estimated to be less than 20 minutes.

Lead foil is used in some propellant charges as a de-coppering agent and may be of concern if released to the environment. Burn-pan studies conducted by the Defence Research and Development Canada-Valcartier (DRDC) using lead-containing propellants indicate that the majority of lead is contained in and around the burn pans (Thiboutot et al., 2012). It was estimated that less than 2% of the lead was volatilized and released to the air. Additional tests examining the fate of lead during burn pan operations are underway by researchers at the U.S. Army Cold Regions Research and Engineering Laboratory.

Maintenance: Periodic inspections are recommended to verify the structural integrity of the burn pans (e.g., no structural warping or corrosion has occurred). It is recommended that the burn pan is emptied after each burn event. This allows for proper documentation of the propellants burned and aids in proper labeling of the waste residue. Users are advised to contact the installation hazardous waste manager to determine appropriate handling and disposal procedures for the residue.

Cost Information: The cost to construct the portable burn pan is estimated at $5,000 with a predicted unit life of 20 years based on material selection and proper use. Additional cost considerations include the maintenance of the burn pans, safety training, and periodic soil sampling/analysis and air monitoring if deemed necessary.

Recommendation: **Recommended for the management of energetic residues at ranges where large caliber, indirect-fire weapon systems are used.**

Key Resources:

ESTCP. 2012. Fact Sheet: A Portable Burn Pan for the Disposal of Excess Propellants. ESTCP ER-201323. http://www.serdp.org, accessed March 14, 2014.

Thiboutot S, Ampleman G, Pantea D, Whitwell S, Sparks T. 2012. Lead emissions from open burning of artillery propellants. In Longhurst JWS, Brebbia CA, eds, Air Pollution XX, pp 273-284. Volume 157 in WIT Transactions on Ecology and the Environment, published by WIT Press, Southampton, U.K.

U.S. Army National Guard. 2012. Best Management Practices for Army National Guard Operational Ranges: Burn Pans Fact Sheet. Provided by the Army National Guard and URS Group, Inc.

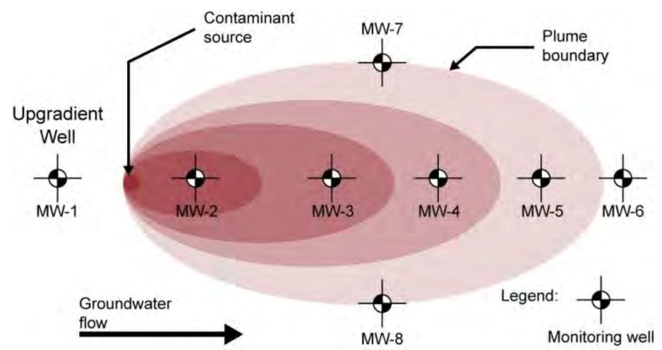
Walsh MR. 2013. U.S. Army ERDC-CRREL, Hanover, NH, personal communication. July.

Walsh MR, Walsh ME, Hewitt AD. 2010. Energetic residues from field disposal of gun propellants. J Hazard Mat 173:115-122.

Walsh MR, Thiboutot S, Walsh ME, Ampleman G, Martel R, Poulin I, Taylor S. 2011. Characterization and Fate of Gun and Rocket Propellant Residues on Testing and Training Ranges. ERDC/CRREL TR-11-13. U.S. Army ERDC-CRREL, Hanover, NH.

Walsh MR, Thiboutot S, Walsh ME, Ampleman G. 2012. Controlled expedient disposal of excess gun propellant. J Hazard Mat 219–220:89–94.

3.10 Monitored Natural Attenuation (MNA)



Recommended groundwater well network for demonstrating MNA (Pennington et al., 1999 [source: USEPA, 1994]).

Description: Monitored natural attenuation (MNA) is defined by the USEPA (1999) as the "reliance on natural attenuation processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods." Natural attenuation processes include physical, chemical, and biological processes such as dispersion, dilution, adsorption, volatilization, abiotic transformation, and biodegradation.

Where It Can Be Used: MNA has been selected as the solution (or part of the solution) at numerous U.S. Department of Defense (DoD) sites impacted with chlorinated solvents, petroleum hydrocarbons, and energetic compounds, such as 2,4,6-trinitrotoluene (TNT) and hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX). However, the authors are not aware of instances where MNA was implemented to manage energetic chemicals in groundwater beneath an operational range.

Advantages: No active groundwater pumping or injection of amendments/materials is required.

Disadvantage: This approach requires a thorough understanding of the plume's shape, information on the rate of release of the energetic chemical to the environment, and variable hydrogeological data. Gathering such data requires installation of monitoring wells throughout the plume. Analytical techniques (e.g., compound specific isotope analysis) may be required to demonstrate and quantify the loss of energetic chemical mass due to biological processes.

Cost Information: Cost information and tools to use in developing site-specific cost estimates for MNA are available from a number of federal agency websites and associated documents (see resources provided below). Additional cost factors may need to be considered when implementing MNA on an operational range (e.g., unexploded ordnance [UXO] clearance costs).

***Recommendation:* MNA should be considered as a management strategy at ranges with energetic chemicals in groundwater. It can be used at both large and small ranges, and when appropriate, it may be the least expensive approach to manage a significant groundwater plume of energetic contaminants.**

Key Resources:

http://www.epa.gov/ada/gw/mna.html, accessed March 6, 2014.
http://toxics.usgs.gov/definitions/natural_attenuation.html, accessed March 6, 2014.
Pennington JC, Zakikhani M, Harrelson DW. 1999. Monitored natural attenuation of explosives in groundwater. ESTCP Completion Report – Project CU-9518. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

3.11 Passive In Situ Mitigation Approach for Groundwater

Installation of zero-valent iron (ZVI) PBR at Cornhusker Army Ammunition Plant (AAP), Nebraska (Johnson and Tratnyek, 2008).

Description: An *in situ* method for managing groundwater impacted by energetic chemicals that combines a passive chemical or biological zone with subsurface fluid flow management.

Where It Can Be Used: Soil is excavated and a wall of permeable material that reacts with the energetic chemicals in the groundwater is installed. The wall (amended zone) removes the energetic chemicals as the groundwater flows through the reactive zone. Both chemical and biological zones have been shown to be effective.

Advantages: The major advantage of the passive *in situ* mitigation approach is that the groundwater can be managed *in situ* with no pumping required and no disposal issues for the treated water.

Disadvantages: Can only be used with relatively shallow impacted groundwater with depths <40 feet. How long a specific reactive zone will function is difficult to predict at present.

Cost Information: Cost drivers for this technology are: (1) the depth of the impacted groundwater, (2) the required thickness of the reactive zone, (3) the mobilization costs for the trenching machinery, (4) disposal costs (if any) for the trench cuttings, (5) the width of the impacted groundwater plume, and (6) anticipated longevity of the reactive zone.

Capital costs for installing a full-scale ZVI PRB to treat explosives-contaminated groundwater at Cornhusker AAP, Nebraska were estimated to be $150/ft^2 of wall and annual operations and maintenance costs (to include monitoring) were $200K (ESTCP, 2008a). Unit costs for an *in situ* mulch biowall have been estimated at $0.08/gallon of contaminated groundwater treated over a 10-year period of operation (ESTCP, 2008b). This cost was based on data from a pilot-scale field demonstration of an *in situ* mulch biowall at Pueblo Chemical Depot, Colorado. For comparison, the investigators estimated a unit cost of $0.11/gallon of contaminated groundwater for ZVI PRB technology.

***Recommendation:* Recommended for the management of shallow, narrow plumes of impacted groundwater. This would be particularly appropriate for managing impacted groundwater from hand grenade ranges (HGRs) and demolition ranges, and it could be used at antitank rocket ranges as well.**

Key Resources:

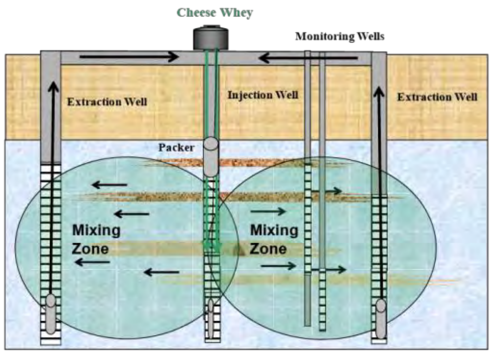
ESTCP. 2008a. Remediation of TNT and RDX in Groundwater Using Zero-Valent Iron Permeable Reactive Barriers. ESTCP Project No. ER-0223 Cost and Performance Report. April. 66 p.

ESTCP. 2008b. Treatment of RDX and/or octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) Using Mulch Biowalls. ESTCP Project No. ER-0426 Cost and Performance Report. April. 47 p.

ITRC. 2011. Permeable Reactive Barrier: Technology Update. June.

Johnson R, Tratnyek P. 2008. Remediation of Explosives in Groundwater Using a Zero-Valent Iron Permeable Reactive Barrier. ESTCP Project No. ER-0223 Final Report.

3.12 Active In Situ Management Approach for Groundwater



Schematic of the semi-passive extraction-reinjection system used at Area 157, Picatinny Arsenal, Dover, New Jersey (Hatzinger and Lippincott, 2012).

Description: Active *in situ* management of groundwater involves the addition of amendments (e.g., electron donors, carbon substrates) to the subsurface to stimulate the microbial growth and degradation of the energetic chemicals of concern.

Where It Can Be Used: Several engineering approaches have been developed to include: (1) "active systems" that meter and mix soluble amendments into groundwater during continuous active pumping, (2) "semi-passive systems" that mix soluble amendments into groundwater during intermittent pumping, and (3) "passive systems" that apply slow-release amendments in trenches, wells, or using direct-push methods, and rely upon natural groundwater flow to mix the amendment with the impacted groundwater (Hatzinger et al., 2009).

Advantages: Active *in situ* management approaches have application for impacted groundwater source zones and as a downgradient cutoff to groundwater migration. The energetic chemicals are treated *in situ*.

Disadvantages: Biofouling of the wells is a frequent problem that must be controlled. Adverse impacts on secondary groundwater quality can be of concern and requires monitoring. The active and semi-passive approaches require aboveground infrastructure, which may be problematic in or near active training areas.

Cost Information: Krug et al. (2009) presents a cost analysis of the three engineering designs for application to perchlorate-contaminated groundwater. Aspects of this analysis should be relevant to estimating the cost of these systems for energetic-impacted groundwater. ESTCP (2012) provides a cost analysis of several *in situ* management approaches for groundwater containing TNT and RDX including: semi-passive bioremediation of the entire plume using cheese whey, a semi-passive biobarrier using cheese whey, passive injection biobarrier using emulsified vegetable oil, a passive trench mulch biowall, and a passive zero-valent iron passive trench barrier.

Recommendation: **Recommended for the management of groundwater source zones and for halting migration of an impacted groundwater plume. Site characteristics (depth to groundwater, hydrogeologic parameters, etc.), management goals, and possible regulatory constraints (due to reinjection of contaminated groundwater) will influence the selection of the optimum engineering approach. This technology would be appropriate for managing impacted groundwater at hand grenade ranges (HGRs), demolition ranges, and antitank rocket ranges.**

Key Resources:

ESTCP. 2012. In Situ Bioremediation of Energetic Compounds in Groundwater. ESTCP Project No. ER-200425 Cost and Performance Report. May. 73 p.

Hatzinger P, Lippincott D. 2012. In Situ Bioremediation of Energetic Compounds in Groundwater. ESTCP Project No. ER-0425 Final Report. March. 240 p.

Hatzinger PB, Schaefer CE, Cox EE. 2009. Active Bioremediation. In Stroo HF, Ward CH, eds, *In Situ* Bioremediation of Perchlorate in Groundwater (SERDP/ESTCP Environmental

Remediation Technology Monograph Series; Ward CH, ed). Springer Science+Business Media, New York, NY, USA. Chapter 6.

Krug TA Wolfe C, Norris RD, Winstead CJ. 2009. Cost Analysis of In Situ Perchlorate Bioremediation Technologies. In Stroo HF, Ward CH, eds., *In Situ* Bioremediation of Perchlorate in Groundwater (SERDP/ESTCP Environmental Remediation Technology Monograph Series; Ward CH, ed.). Springer Science+Business Media, New York, NY, USA. Chapter 10.

3.13 Hydraulic Control

Hydraulic control (e.g., pump-and–treat) system at the Lagoons Groundwater Plume at Umatilla Chemical Depot, Oregon (photograph provided courtesy of Harry Craig, U.S. Environmental Protection Agency Region 10).

Description: Hydraulic control refers to the use of extraction wells to pump impacted groundwater aboveground where it can be managed using various technologies.

Where It Can Be Used: This technology can be used as a source control option or at an installation boundary to prevent the migration of impacted groundwater. The effectiveness of pump-and-treat is dependent on a number of factors, including the geologic conditions and groundwater flow parameters. Characteristics such as site stratigraphy, degree of heterogeneity, structural geology, hydraulic conductivity, vertical flow, and distribution of the energetic compounds must be considered when assessing this technology.

Advantages: This technology, while expensive, is effective at halting the migration of impacted groundwater and allows for the reliable removal of energetic chemicals from the groundwater, typically by using granulated activated carbon (GAC).

Disadvantages: Disadvantages include the high capital costs for installation of the extraction wells and construction of the aboveground management system, and the annual operation and maintenance (O&M) costs of pumping groundwater to the surface and treating for extended periods of time. Siting pump-and-treat aboveground infrastructure on an operational range without interfering with training activities may be problematic. The efficacy of pump-and-treat can be adversely impacted by subsurface heterogeneities, fractured bedrock and zones of low hydraulic conductivity.

Cost Information: Total estimated costs for extraction, treatment, and long-term monitoring of the J1 northern and southern plumes at Massachusetts Military Reservation (MMR) are $4.9M and $14.6M, respectively, with the time required to reduce contaminant levels to risk-based acceptable concentrations estimated at 14 and 37 years, respectively (USEPA, 2011).

***Recommendation:* Use of hydraulic control appears to be a last resort for training range applications for situations where other management options are not possible or are ineffective, and/or an important receptor such as a sole-source aquifer must be protected.**

Key Resources:

ESTCP. 2004. Application of Flow and Transport Optimization Codes to Groundwater Pump-and-Treat Systems. ESTCP Cost and Performance Report Project CU-0010. January.

USEPA. 1997. EPA Ground Water Issue: Design Guidelines for Conventional Pump-and-Treat Systems. EPA/540/S-97/504. USEPA Office of Solid Water and Emergency. September.

USEPA. 2011. EPA Reaches Cleanup Decision for J1 Range and Groundwater Plumes at Camp Edwards. Press Release. May 31. Available at http://yosemite.epa.gov/opa/admpress.nsf/0/ED524B82E3040B36852578A100578A21, accessed March 6, 2014.

3.14 Constructed Wetlands

Pilot-scale constructed wetland at Milan AAP, Milan, Tennessee (ESTCP, 1999)

Description: A constructed wetland is a form of hydraulic control where impacted groundwater is pumped to the surface and passed through an artificial wetland that has been designed to remove energetic compounds as the water flows through the wetland.

Where It Can Be Used: Constructed wetlands are designed to mimic the powerful cleansing effects of natural marsh ecosystems by relying on different aerobic and anaerobic conditions with various aquatic plant species.

Advantages: The major advantage of this system is that it combines both plant-based mitigation with anaerobic/aerobic cycling to remove both nitroaromatic and nitramine compounds from the groundwater.

Disadvantages: The main disadvantage of this management approach is the high annual operation and maintenance (O&M) costs of pumping groundwater to the surface. For removing energetic compounds, an energy source such as molasses must be added to create anaerobic conditions. The constructed wetland technology is also temperature dependent and implementation at sites in colder climates may be problematic.

Cost Information: A pilot-scale constructed wetland system was tested at Milan Army Ammunition Plant (AAP), Tennessee. Based on data collected during this demonstration, the total cost (capital and O&M) for a 10-acre, full-scale, gravel-based wetland system designed to treat 200 gallons per minute (gpm) of contaminated groundwater was estimated at $1.78 per thousand gallons of groundwater (ESTCP, 1999). The reported costs do not include the cost of well construction.

Recommendation: **This is a very expensive technology and does not seem to have an advantage over classical hydraulic control systems using granulated activated carbon (GAC) for managing impacted groundwater. The only potential application for energetic residues on ranges seems to be the management of surface water drainage from a detonation area**.

Key Resources:

ESTCP. 1999. The Use of Constructed Wetlands to Phytoremediate Explosives-Contaminated Groundwater at the Milan AAP, Milan, Tennessee. ESTCP Project CU-9520 Cost and Performance Report. July. 46 p.

Appendix A – Acronyms and Abbreviations

µg/L	microgram(s) per liter
2,4-DNT	2,4-dinitrotoluene
AAP	Army Ammunition Plant
BMP	best management practice
CFB	Canadian Forces Base
CSIA	compound specific isotope analysis
Ctr	contractor
DoD	U.S. Department of Defense
EOD	explosive ordnance disposal
ESTCP	Environmental Security Technology Certification Program
GAC	granulated activated carbon
gpm	gallon(s) per minute
HGR	hand grenade range
HMX	octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
HTRW	hazardous, toxic, and radioactive waste
kg	kilogram(s)
L	liter(s)
m	meter(s)
MC	munitions constituent
MEC	munitions and explosives of concern
MIS	*MULTI INCREMENT*® sampling
mm	millimeter(s)
MMR	Massachusetts Military Reservation
MNA	monitored natural attenuation
O&M	operation and maintenance
OB/OD	open burn/open detonation
ORAP	Operational Range Assessment Program
PMSO	peat moss and soybean oil

PRB	permeable reactive barrier
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazine
SAR	small arms range
SERDP	Strategic Environmental Research and Development Program
TNT	2,4,6-trinitrotoluene
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
UXO	unexploded ordnance